

Hot Subdwarfs from SDSS and SPY

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Abstract. We present the results of quantitative spectral analysis of subdwarf O stars (sdO) obtained from the SDSS database. By visual inspection, 112 sdO stars could be identified in a set of spectra of photometrically selected faint blue stars. Fitting the Balmer, He I and He II lines to state-of-the-art non-LTE model spectra, we derived their effective temperatures, surface gravities and helium abundances. We find the helium-enriched sdO stars to rally in a small intervall of $T_{\text{eff}} = 40\,000\text{ K} \dots 50\,000\text{ K}$ and $\log g = 5.5 \dots 6.0$, whereas the helium-deficient ones are showing a wide variance both in temperature and $\log g$. A puzzling feature is a significant number of helium rich subdwarfs below the helium main sequence. These stars would not be able to burn helium in their cores and pose a serious problem to subdwarf evolution theories. We conclude, that the sdB stars are linked with the helium-deficient sdO stars, i.e. the sdBs are predecessors for the helium-deficient sdOs. To explain the helium-enriched sdO stars in their entirety, we regard two scenarios as most promising: The merging of two helium-core white dwarfs and the late hot flashers. To investigate this further, we started an NLTE analysis of carbon abundances. So far, we find carbon slightly enriched above solar, but no trends can be seen yet.

1. Introduction

We distinguish spectroscopically between the cooler sdB stars ($T_{\text{eff}} < 40\,000\text{ K}$) showing He I lines and the hot sdO stars ($T_{\text{eff}} > 40\,000\text{ K}$), with He II lines. Recent work of Ströer et al. (2007) suggests a strong correlation of the helium abundance with carbon/nitrogen line strengths. A physically more meaningful classification into ‘helium-enriched sdO’ for stars with supersolar helium abundance and ‘helium-deficient sdO’ for subsolar abundances is suggested.

While the sdBs form a homogenous group, the sdOs show a wide spread in temperature, gravity and helium abundance. Only a few stars are helium-deficient but the helium-enriched sdO stars are represented in great number. Canonical theories see an evolutionary link between sdO and sdB stars, though the mechanism driving the hydrogen-rich sdB atmosphere into a helium-rich sdO in the course of stellar evolution is hard to explain.

We are interested in the sdO stars, particularly their evolutionary status, their origins and possible evolutionary links between them and the cooler sdB stars. Recent work in this field has been carried out by Ströer et al. (2007) using the high resolution spectra of 46 sdO stars from the ESO SPY survey

(Napiwotzki et al. 2001). We will take advantage of the huge database of the ongoing Sloan Digital Sky Survey which provides spectra of many different objects, among them a number of sdOs. By comparing and combining our results with the results from Ströer et al. (2007), the sample size will be large enough to test rivalling theories for their origin and evolution

2. Quantitative Analysis of SDSS Spectra

From the database of the 5th data release (DR5) of SDSS, we selected all point sources within the colour box $(u - g) < 0.4$ and $(g - r) < 0.1$. We classified more than 8 000 spectra by visual inspection, mostly white dwarfs, about 500 sdB stars and 112 sdOs. After sorting out spectra with spectral features indicative of a cool companion star or of too low signal-to-noise, we carried out a spectral analysis of the remaining 86 of our programme stars. A model atmosphere fit was conducted in order to obtain the effective temperature, surface gravity and helium abundance.

2.1. Model Atmosphere Fitting

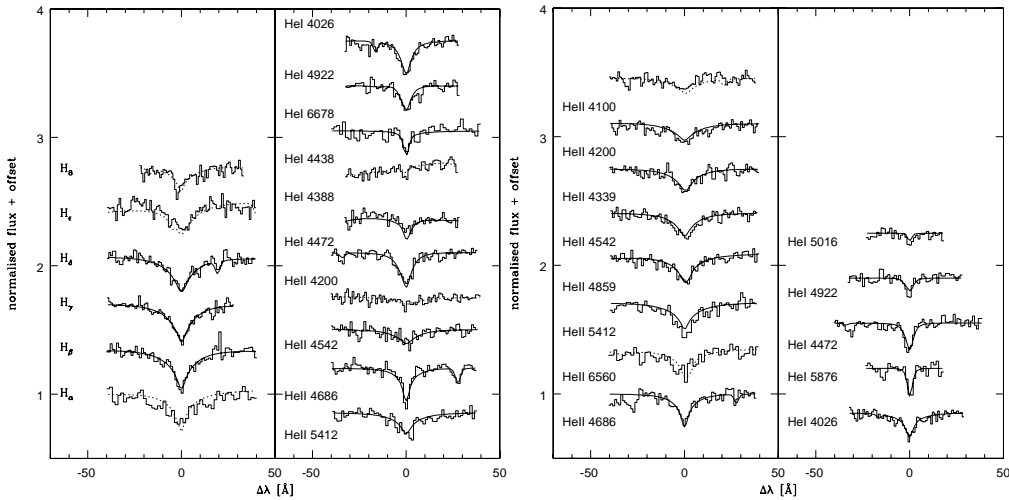


Figure 1. Examples of NLTE model fits to sdO spectra from SDSS. *Left hand side:* a helium-deficient sdO. *Right hand side:* a helium-enriched sdO. The observed spectra are displayed as histograms. Lines that are not fitted but only displayed for inconsistency checks are plotted as dashed lines.

To determine T_{eff} , $\log g$ and $\log(\frac{N_{\text{He}}}{N_{\text{H}}})$ of the stars, we fitted synthetic model spectra to the observed ones, using a χ^2 -minimization procedure (Napiwotzki 1999) to derive all three parameters as well as the radial velocity simultaneously. The synthetic non-LTE models were constructed using the PRO2 code (Werner & Dreizler 1999) with a new temperature correction technique (Dreizler 2003) and include partially line blanketing. It includes H and He atoms only. The model grid ranges in temperature from 30 000 K to 100 000 K and from 4.8 dex to 6.4 dex for $\log g$ with $\log(\frac{N_{\text{He}}}{N_{\text{H}}}) = -4 \dots +3$. No extrapolation beyond

the model grid was allowed. Due to the inconsistencies reported for the H_α -line of some sdB stars, which might be caused by a stellar wind (Heber et al. 2003), this line was never fitted to the models, but it was always plotted to search for peculiarities. H_β to H_γ and He II 4859 Å and 4339 Å were always fitted, but we found He II 4100 Å often too weak to provide a reasonable fit. The ionization equilibrium of He II and He I is very sensible to temperature, therefore we always included He I 4472 Å, even in its absence.

2.2. Considering the Errors

The fit program provided us with mere statistical errors, they range from $\Delta T_{\text{eff}} \approx 150 \dots 3000$ K, depending on the signal-to-noise ratio. Fortunately, six stars were observed twice (see Table. 1), which we can use to estimate the quality of our fits. The differences in parameters obtained from spectrum A and spectrum B lie within the given statistical errors, which we therefore conclude to be robust.

Table 1. Two exposures had been taken from six of our programme stars. We use this opportunity to check the reliability of the errors.

SDSS designation	T_{eff} [K]	$\log g$ [cm s ⁻²]	$\log(\frac{N_{\text{He}}}{N_{\text{H}}})$
SDSSJ 00:51:07.01+00:42:32.5	38234±330	5.73±0.06	-1.07
	38207±305	5.72±0.05	-0.94
SDSSJ 11:14:38.57-00:40:24.1	57714±3268	5.56±0.19	-0.94
	55730±2292	5.56±0.15	-0.86
SDSSJ 16:37:02.78-01:13:51.7	45547±338	5.77±0.08	+3
	45860±353	5.70±0.08	+3
SDSSJ 17:00:45.67+60:43:08.4	47404±1870	5.92±0.16	+2.26
	49537±2911	6.09±0.17	+2.17
SDSSJ 23:35:41.47+00:02:19.4	69906±2234	5.45±0.08	+1.10
	72870±1341	5.44±0.11	+1.18
SDSSJ 23:39:13.99+13:42:14.2	48592±1540	5.82±0.15	+0.92
	48914±3233	5.66±0.18	+1.19

2.3. Results and Comparison to the SPY Sample

We now compare our SDSS sample to the 46 stars of the SPY sample. We find that the ratio of helium-enriched stars to helium-deficient ones is higher in SDSS than in SPY (68:18 vs. 33:13). In addition, the SDSS sample contains more very hot stars ($T_{\text{eff}} > 60\,000$ K) than the SPY sample. Both findings are probably due to selection effects, e.g. the limiting magnitude of the surveys, which is considerably fainter for SDSS than for SPY. Besides that, the distributions of the SDSS and the SPY sample in the $T_{\text{eff}}\text{--}\log g$ plane are very similar, as can be seen from Fig. 2. We will therefore merge the samples for further discussion.

None of the programme stars is located on the EHB, meaning that either they are post-EHB stars, most likely evolved from the sdB stars, or they do not have any link to the EHB at all and are just evolving through this region in the HR diagram. The helium-enriched sdOs are spread over $T_{\text{eff}} =$

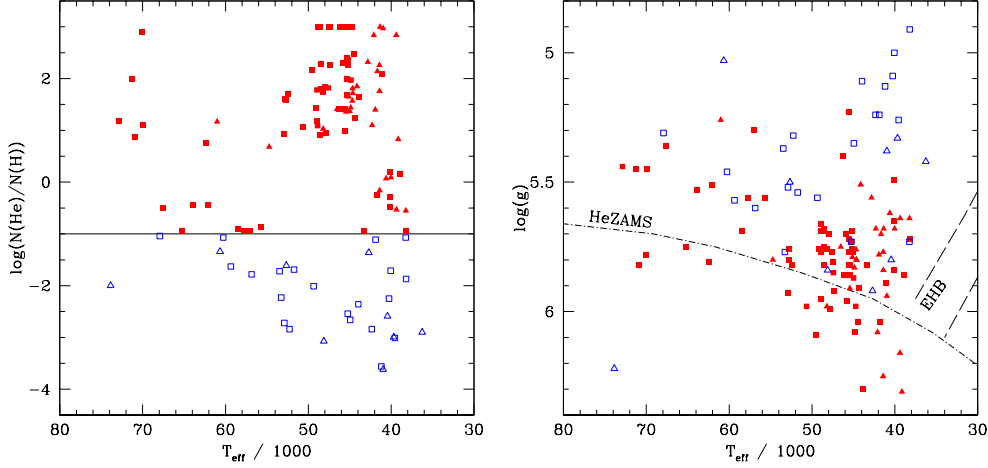


Figure 2. *Left:* $T_{\text{eff}}\text{--}\log(\frac{N_{\text{He}}}{N_{\text{H}}})$ diagram. The solid horizontal line represents the solar helium abundance. *Right:* $T_{\text{eff}}\text{--}\log g$ diagram. Also given is the helium main sequence (HeZAMS) as well as the EHB, defined by the location at zero age and terminal age. Filled symbols represent helium-enriched stars, while the open symbols are helium-deficient ones. Squares are stars from SDSS, triangles are stars from SPY.

40 000 K... 74 000 K and $\log g = 5.2 \dots 6.3$, but a concentration of them within the small temperature interval $T_{\text{eff}} = 40\,000\text{ K} \dots 50\,000\text{ K}$ becomes apparent, only a few stars are found to lie at hotter temperatures. The hydrogen-rich sdOs on the other hand shun this region.

Note that both the SDSS and the SPY sample contains stars lying below the helium main sequence, all but one are helium-enriched. These stars cannot sustain stable helium burning in their cores and therefore it is difficult to explain their origin.

3. Stellar Evolution Tests Using the Combined Samples

Two different approaches to hot subdwarf star evolution are presented in the literature: *(i)* binary star evolution and *(ii)* single star evolution. Both are trying to explain the high mass loss the stars have to suffer from before reaching the EHB. In the context of binary star scenarios, this is achieved by mass exchange in sufficiently close systems, whereas single star scenarios have to invoke physical mechanisms within the star itself, like unusually strong stellar wind, mixing, etc.

3.1. Binary Star Evolution

Han et al. (2002, 2003) did an extensive binary population synthesis and found three formation channels relevant for the sdB/sdO population: stable Roche lobe overflow, common envelope ejection and a merging of two helium-core white dwarfs. While the first two scenarios result in relatively cool stars preferentially lying between 30 000 K and 40 000 K, our sdO stars are very unlikely to have followed the latter formation channel as they are mostly hotter.

For sdO stars, especially the helium-enriched ones, we regard the formation via a merging of two helium WDs as most promising. Short period binary WDs will lose orbital energy through gravitational waves. With shrinking separation, the less massive object will eventually be disrupted and accreted onto its companion, leading to helium ignition. Saio & Jeffery (2000) argue, that this merger product will result in a helium burning subdwarf showing an atmosphere enriched in CNO-processed matter. This scenario therefore can explain these extremely helium-enriched sdOs showing strong nitrogen lines in their atmospheres. However, Gourgouliatos & Jeffery (2006) find that, under the assumption of total angular momentum conservation, He+He WD merger do rotate faster than breakup velocity. A mechanism that enables the star to get rid of its angular momentum still has to be found.

However, there is another possible origin for hot subdwarf stars. The sdB HD 188112 is reported to have a mass of $0.23 M_{\odot}$, based on a Hipparcos parallax measurement, too low to sustain core helium burning (Heber et al. 2003). Such a star may have formed if mass transfer occurred on the first red giant branch (RGB) and before the onset of core helium burning.

Appropriate tracks have been calculated by Driebe et al. (1998), who evolved a $1 M_{\odot}$ main sequence star as one component of a binary system through the RGB stage without ignition of helium to a helium star and eventually to a helium core white dwarf, under the assumption of mass transfer to the companion. The evolution of such stars with masses between $0.414 M_{\odot}$ and $0.300 M_{\odot}$ would lead straight through the observed sdO population, down to below the HeZAMS. However, how compelling these findings may be, they suffer from a fundamental discrepancy: Napiwotzki et al. (2004) find that the fraction of radial velocity variable stars among the helium-enriched sdOs is 4 % at most. Also, the predicted helium abundance is much lower than for the helium-enriched sdOs suitable for this scenario and within the relevant mass range, no enrichment of the atmosphere with processed matter from the interior is predicted.

3.2. Single Star Evolution

The canonical evolution theory considers sdO stars to be the progeny of the sdB stars irrespective of their helium content. Thus a star reaching the EHB will evolve from the EHB towards the sdO regime with higher temperatures and eventually to the white dwarf cooling curve. Such tracks have been calculated by Dorman, Rood & O'Connell (1993). They started with a star at the tip of the RGB and calculated the minimum core mass needed to ignite helium burning, then added a small envelope. The needed core mass varies slightly and ranges from $0.464 M_{\odot}$ for supersolar to $0.495 M_{\odot}$ for subsolar metallicity, while the envelope mass is very small ($M_{\text{env}} \leq 0.002 M_{\odot}$). Still, the question for the cause of the mass loss remains unanswered. In Fig. 3 we compare three post-EHB evolution tracks to the observed distribution. They follow the evolution from the zero age horizontal branch, where core helium burning starts, to the terminal age horizontal branch, and beyond, for stars with 0.471, 0.473 and 0.475 solar mass cores. Because of the small envelopes, the post EHB evolution hydrogen shell burning is insignificant and therefore the star does not climb the AGB (ABG manqué stars), but evolves through higher temperatures until eventually it settles on the white dwarf cooling curve. These post-EHB tracks cover the sdB

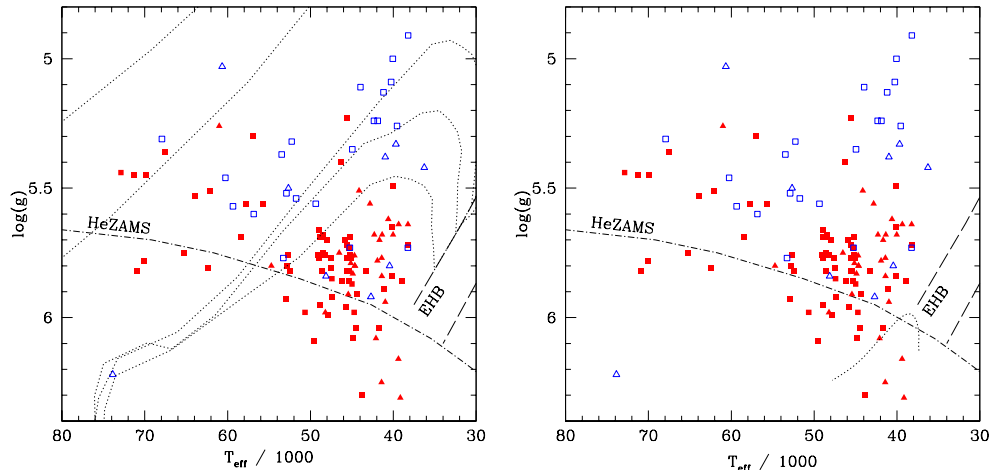


Figure 3. *Left:* Comparison of our sample to three post-EHB tracks (Dorman, Rood & O'Connell 1993) for $0.475 M_{\odot}$, $0.473 M_{\odot}$ and $0.471 M_{\odot}$ (top to bottom). In the upper left two post AGB tracks (Schönberner 1983) for $0.565 M_{\odot}$ and $0.546 M_{\odot}$ (left to right) are shown as well. They may explain a few of the very hot sdO stars. *Right:* A track of a late hot flasher after it has settled onto the EHB is plotted (Sweigart 1997; Moehler et al. 2002). Symbols as in Fig. 2.

regime as well as the lower gravity helium-deficient sdO stars at $T_{\text{eff}} \geq 40\,000$ K. This is consistent with the helium-deficient sdO stars being the descendents of the sdB stars.

However, some of the hottest stars and in particular the helium-enriched stars which cluster at $T_{\text{eff}} = 45\,000$ K do not fit into this scheme. The very hot sdO stars may be explained as post-AGB stars on their way to the white dwarf cooling curve. Two such tracks calculated by Schönberner (1983) are shown in Fig. 3. But due to the very short evolutionary timescales ($\sim 30\,000$ yrs from ejection of the planetary nebula to pre-white dwarf settling) for the post-AGB stars, we expect only a few such stars in our sample.

For the helium-enriched sdOs on the other hand, we have to find another mechanism that explains both their distribution as well as the peculiar carbon/nitrogen line strengths in connection with the high helium abundances. Sweigart (1997) and Brown et al. (2001) analyzed a scenario for stars called late hot flasher. They argue, that fast rotation of RGB stars could lead to mixing of helium into the envelope, resulting in a higher RGB peak luminosity and therefore to higher mass loss rates on the RGB. This will delay the helium flash until the star has left the RGB and is already descending on the white dwarf cooling curve. The delayed flash will induce mixing which will transport hydrogen into the helium burning core where it is burnt, resulting in a helium-enriched star with $T_{\text{eff}} \approx 40\,000$ K on or near the helium main sequence and enriched in carbon.

We have plotted an evolutionary track resulting from a late hot flasher in Fig. 3. Also this track fails to reproduce the observed distribution, though the very late hot flasher scenario can explain stars below the helium main sequence.

4. Carbon Abundances from High-Resolution Spectra (SPY)

It is clear now, that the helium abundance and the $T_{\text{eff}}\text{--}\log g$ diagram alone cannot answer the question as to the sdOs' origin. As different scenarios predict different abundance patterns in particular for carbon and nitrogen, we started with a carbon abundance analysis of high resolution spectra of the sdO stars from SPY. The new models include C III and C IV in addition to hydrogen and helium. They were calculated and fitted to the observed spectrum using the same methods as described above.

4.1. Preliminary Results

So far we have investigated seven helium-enriched sdOs. All stars are slightly enriched in carbon, with $\log(\frac{N_{\text{C}}}{N_{\text{total}}}) = -2.6 \dots -3.0$, compared to the solar value of $\log(\frac{N_{\text{C}}}{N_{\text{total}}}) = -3.5$. However, when fitting the carbon lines, two stars showed a significant line broadening indicating projected rotational velocities of 25 km s^{-1} (see Fig. 4) and 30 km s^{-1} , which is surprising as most sdB stars do not show $v_{\text{rot}} \sin i > 10 \text{ km s}^{-1}$ (see Geier et al., these proceedings). Though low number statistics, this might be considered another hint pointing towards the assumption that sdB stars and helium-enriched sdO stars are two different populations that formed by different evolutionary paths.

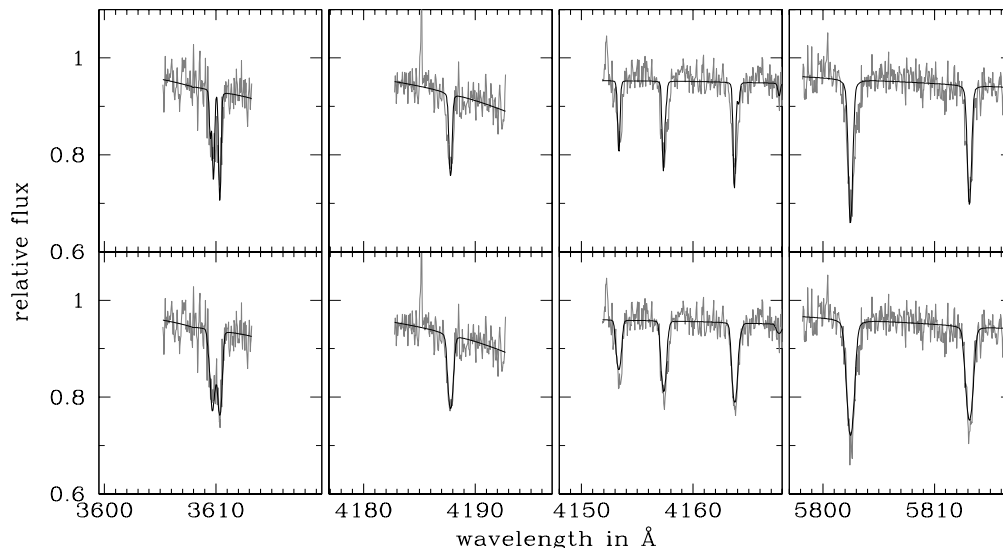


Figure 4. Line fits to C III 3609.0, 3609.6 Å, C III 4186.9 Å, C III 4152.4, 4156.5, 4162.8 Å and C IV 5801.3, 5812.0 Å (from left to right). Top panels: No rotational broadening, bottom panel: $v_{\text{rot}} \sin i = 25 \text{ km s}^{-1}$.

5. Summary and Conclusion

We have fitted synthetic NLTE model spectra to 87 sdO spectra from the SDSS database, using a χ^2 technique. While the helium-enriched stars cluster in a relative small regime around $T_{\text{eff}} = 45\,000 \text{ K}$, the helium-deficient sdO stars are

widely spread. Worth noting is a significant number of helium-deficient sdOs *below* the helium main sequence, a fact that cannot be explained by canonical evolution.

Preliminary results of a carbon abundance analysis shows slightly supersolar values for seven helium-enriched sdOs. The higher $v_{\text{rot}} \sin i$ we found in two of them compared to the very slowly rotating sdBs might be an additional support for the merger scenario.

By comparing the stars' distribution in the $T_{\text{eff}}\text{--}\log g$ diagram to several evolutionary paths, we conclude that most likely the helium-deficient sdO stars are the progenies of the sdB stars. The helium-enriched sdO stars still pose a problem: The late hot flasher scenario as well as the white dwarf mergers qualify as formation channels as they predict an enrichment of helium and carbon/nitrogen. The merger scenario is attractive because it can also naturally explain the absence of radial velocity variables (close binaries) amongst the helium-enriched sdOs.

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